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Performance Assessment of Pressurized Stairs in High Rise Buildings

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Pressurized stair cases are an important part of the Fire Safety Strategy of high rise buildings. Long egress times are compensated by creating safe environments within egress staircases allowing considering the displacement time within those stairs as time where occupants can be considered safe. The main mechanisms by which stairs are "made safe" are by guaranteeing structural protection of the enclosure and by elevating the pressure within the stair to ensure that smoke can not enter. Despite the critical importance of this element of the Fire Safety Strategy, the analysis and implementation of these systems remain simplified. Simple models have been developed using Bernoulli type formulations that account for static pressure and empirical constants to calculate flows through doors and other leakage areas. Implementation of these systems is even more simplified, consisting mainly of a direct feedback loop that controls a fan output on the basis of a pressure measurement inside the stair. The flow induced by the fan guarantees a minimum pressure. The pressure inside the stair needs to be limited to enable doors to be open, thus pressure dampers are introduced to release airflow in the event the pressure exceeds a specified maximum. Validation of these methodologies was done in the 70's and 80's with very limited field validation in real systems. This study presents an assessment of the performance of pressurized staircases in six high rise buildings. All systems have been designed using a similar methodology but implemented in different ways. In all cases the control mechanism for the fan is a direct feedback loop from a single pressure sensor. The results have been evaluated showing the limitations of the control system in the event of multiple doors being opened and the limitations of the pressure release dampers (as a response mechanism) if the pressure becomes unstable.

1. Introduction

The design of pressurization systems consists in the quantification of the required air flow that will compensate leaks and enable the staircase to remain at a higher pressure than ambient. This will prevent the smoke from entering the staircase and result in a safe environment for those evacuating and fire fighters potentially using the staircase during their intervention procedures. This is a critical component of the fire safety strategy for most complex structures, such as high rise buildings, where maximum egress distances can only be achieved to the staircase and not to the exterior.

Calculation methods for the required air flow have been developed and have been included in standards such as ASHRAE [1] and NFPA [2]. The calculations are mostly based on a simple mass balance within the stair enclosure using empirical constants that enable the estimation of the different exiting flows. The main objective is to keep the pressure within a range that enables unobstructed opening of doors and prevents the smoke from entering the enclosure. This establishes upper and lower pressure thresholds that need to be respected. The empirical constants used for these calculations have been obtained from tests in idealized conditions [3], therefore their validity to real applications needs to be assessed.

Consideration of the potential flow paths within the building is necessary to quantify the mass balance for the enclosure that enables, via the ideal gas law, to establish the internal pressure. Complex CFD calculations are not a viable option, because every leakage area will have to be described with precision. Instead, simplified treatments have been developed. The details of the flow paths have been summarized in effective areas of leakage that provide estimates of the overall flow from the staircase to the exterior.

Important elements are the doors used for access and egress from the stair. These doors represent a large surface area, thus engineering solutions should cope with the possibility of a number of open doors. Given that the pressure has to be bounded, the number of allowed open doors and their configuration with respect to the building geometry represents a critical choice when engineering these systems. Furthermore, opening and closing of doors can potentially affect the effective area of leakage because doors can close differently

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when the stairs are pressurized. Therefore, the required set of empirical constants used to quantify these simplified flow systems can evolve in a complex manner. The most commonly used set of constants emerged from the studies by Tamura and Wilson [4], Tamura and Shaw [5] and Shaw et al [6] and is currently tabulated in Chapter 51 of the ASHRAE Handbook [1].

A final complexity to the design process of pressurized staircases is the lack of homogeneity of finishing and door installation. There is always the potential that all doors will leave different leakage areas and that the finishing of the stair may allow for unaccounted leakages. Therefore testing and calibration of the pressurization system is always necessary.

The potential variations associated to unidentified leakage areas, to the complexity of the building and to the unpredictable number of opened doors is accounted by over dimensioning the intake flow and introducing automatic control systems to maintain the pressure within the require limits. Pressure dampers are introduced to limit the pressure rise below the upper bound. While these techniques are commonly used, the solutions are generally very simple, dampers tend to be simple mechanical dampers and control systems tend to be single input linear systems. To be able to design more robust and sensitive systems it is necessary to be able to characterize adequately each specific stair.

This study takes a series of six existing concrete buildings and conducts a series of performance assessment studies. The systems are all conventional arrangements with mechanical dampers and single input control loop for the incoming airflow. The objective is to define the capability of these systems to respond to different operating conditions and to provide an example of the detail necessary to sufficiently characterize the response of such systems so that more complex control algorithms could be designed.

2. Summary of Calculation Methods

The design of pressurization systems consists in the quantification of the required air to be supplied to compensate for leaks increasing the pressure beyond a pre-specified threshold. The thresholds have been predetermined on the basis of experimentation. This section will present a brief summary of the calculations extracted from Klote and Milke [3].

The minimum pressure required to prevent smoke entering the staircase (ΔP_{SB}) is a direct function of the size of the fire. The fire will establish a pressure difference that needs to be compensated by the increased pressure of the stairwell. The bigger the fire (the higher the temperature of the smoke) the larger the pressure differential required to prevent migration of smoke into the stairwell. A sprinkler system is expected to control the fire and to cool down the temperature of the combustion products, therefore, NFPA 92A (Table 5.2.1.1) [2] allows for a decrease in the required pressure in the presence of sprinklers. For the present building characteristics and according to NFPA 92A, with sprinklers a minimum of 12.5 Pa (0.05 in w.g) are necessary to prevent smoke from entering the stair. In the absence of sprinklers, the recommended value will be double, i.e. 25.0 Pa (0.1 in w.g)

The maximum allowable pressure is defined by a characteristic force that a person is capable of exerting on a door. NFPA 101 [7] specifies an empirical value of 132 N (30 lbf). The ASHRAE handbook [1] provides the following expression for the force resulting from balancing moments around the door hinge:

$$F = F_{dc} + \frac{5.20 WA\Delta p}{2(W-d)}$$

Where

F	Maximum allowable force (30 lbf)
Fdc	Force required to overcome the self-closing mechanism (10 lbf)
W	Door width (2,95 ft)
A	Door area (21 ft2)
ΔP	Pressure differential across the door
d	Distance from the hinge to the edge of the door (0,25 ft)

The values indicated are typical values for the doors of this study and the formula is expressed in imperial units to be consistent with the ASHRAE Handbook [1]. For a door the maximum allowable pressure could then be calculated, which for a typical case of this study will give 86.5 Pa (0.35 in.w.g).

The design calculations associated with the flow necessary to keep the pressure above the minimum required (Q) considers two main factors. First is the flow from the stair through the building and to the outside and second is the temperature difference between the interior and exterior of the building.

The flow from the stair through the building and to the outside is calculated using Bernoulli's equation. For this purpose the pressure differences between the stair and the building (ΔP_{SB}) and the building and the outside need to be established ((ΔP_{BO}). The pressure difference between the stair and the building is the design requirement while ΔP_{BO} results from mass conservation and Bernoulli's equation.

If there is a temperature difference between the inside and outside of the building, the pressure differences will vary at each floor because of the density diferences. The variation is accounted for by means of the following expression:

$$\Delta P_T = by$$

Where

$$b = K_s\left(\frac{1}{T_O} - \frac{1}{T_S}\right)$$

y	Height
b	Temperature factor
T_O	Inner absolute temperature
T_S	Outer absolute temperature
K_s	Gravity/Density constant (7.64)

The set of equations is simple and it can only be slightly complicated by the multiple possible flow paths. If all flow paths are adequately characterized then a value of Q that can guarantee the minimum required pressure can be calculated. Unfortunately, the characterization of all flow paths is not possible for each building, even more, not at the design stage, therefore a simpler approach needs to be followed. The methodology thus establishes two simple characteristic leak areas that guarantee the flow from the stair into the building (A_{SB}) and from the building to the outside (A_{BO}). These paths lead to an effective leakage area (A_{SOe}) defined by:

$$A_{SBOe} = \frac{A_{SB}A_{BO}}{\sqrt{A_{SB}^2 + A_{BO}^2}}$$

Characteristic values can be obtained from the ASHRAE Handbook, Chapter 51 [1] for different configurations. Typical values for A_{SB} and A_{BO} have been obtained experimentally. Observation of the different values available clearly indicates that openings to the outside will have a dramatic effect on the effective areas as will the opening of the doors between the stair and the building. Furthermore, the relative location of the door with respect to the outside will also have a significant effect (i.e. a door leading to a corridor within a section of the building that has no openings to the outside will have a much smaller effect than one leading directly to the outside).

Independent of the specific thresholds or detailed criteria used, the design of a pressurization system is constrained by the range of pressures indicated above. The closer the minimum pressure is to the maximum allowable pressure the more sophisticated the control mechanism required.

The choice of number of doors to be opened for the design calculations is intimately linked to the fire safety strategy. If a robust mechanism to control the maximum pressure rise is implemented, then the system can be over dimensioned by opening all doors to calculate Q. This will be consistent with a situation where an alarm will initiate simultaneous evacuation of all floors. If the pressure maximum cannot be controlled adequately or the designer wants to avoid over dimensioning the fan, then the system can be designed considering less doors open. This is a valid strategy if implemented with an alarm system that stages evacuation. An alternative strategy is to introduce automatic control mechanisms that can regulate the flow and pressure release to maintain the pressure within the required range. This is the preferred strategy, where a reduced number of open doors are considered to select the fan, venting is guaranteed by dampers and an automatic control mechanism is implemented to define the flow of the fan as needed.

This approach, while simple, is capable of providing a robust design criterion for Q if the system can be controlled within the minimum and maximum pressure range. Thus the purpose of this study is to establish how robust these simple systems are and if the control mechanisms are capable of maintaining the pressure inside the staircase within the desired range.

3. Description of the Buildings

The buildings to be studied are a set of six concrete structures part of a single business complex. The name and location of the buildings will be withheld not to compromise the privacy of the owners that allowed the tests to be conducted. The buildings were built within a decade and different designers defined the characteristics of the pressurization systems. The main characteristics of the buildings are presented in Table 1.

The exterior finishing of the buildings is different in each case, with most buildings counting with complex external glazing arrangements. While all buildings are offices the interior distribution also varies dramatically among the different structures. The dimensions of the stairs are also different given the individual egress requirements.

Building	Floors	Stairs Leading to the Building	Stairs Leading to a Lobby	Stairs leading directly outside
A	5	3	1	1
B	12	11	1	0
C	19	18	1	0
D	21	19	1	1
E	18	16	1	1
F	18	16	1	1

Table 1 Main characteristics of the buildings

Figure 1 shows simplified schematics of all six buildings. These schematics indicate the relevant details of each building.

The control system of all staircases consists of the exactly the same approach. A series of mechanical dampers are intended to maintain the pressure below the acceptable maximum. A single pressure transducer is used to monitor the pressure and serve as input to a linear control system that operates a frequency regulator for the fan. All systems are connected to the alarm system that enables both manual and automatic start-up of the system. In all cases this has been designed in accordance to NFPA 72 [8].

A typical design protocol was followed for each building leading to the design flow rates presented in Table 2. These values are only indicative to provide the reader with an estimate of the size of each fan and the characteristics of each building.

As observed in Table 2, doors leading to the outside have significantly higher flow rates than those leading into offices and lobby. Open doors have much larger flow rates, thus the reference case of all closed doors will result in a design flow rate that will be extremely small. The choice of number of doors open used for design purposes remains to some extent arbitrary, thus in this case the number of doors open was chosen to fit the fire safety strategy. None of the buildings have been designed for staged evacuation, thus a significant number of open doors is to be expected. It is important to note that these calculations are only indicative to provide the reader with estimates of what the calculation process during design could have potentially given as results.

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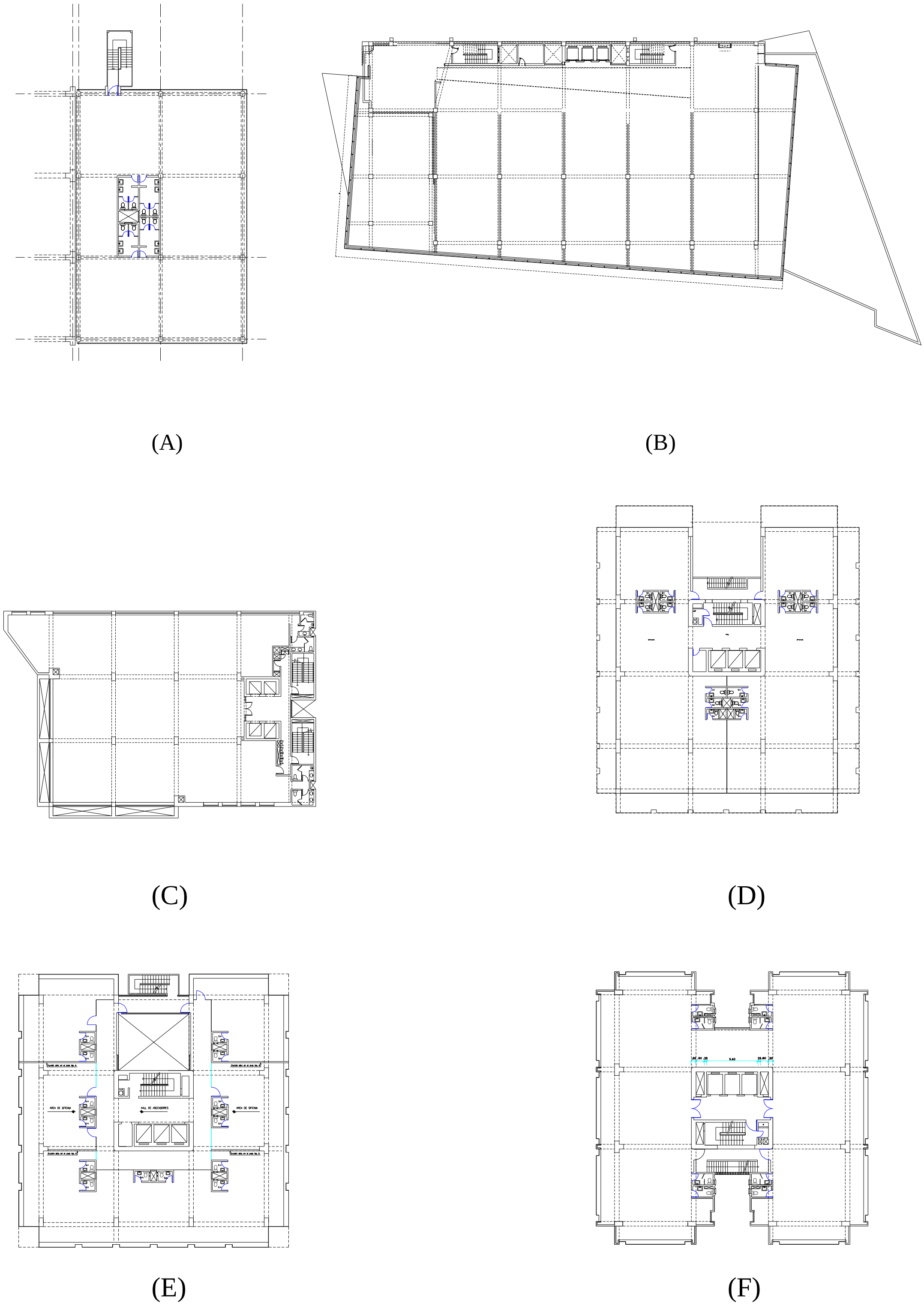

Figure 1 Schematics of the different building layouts. The labelling corresponds to that of Table 1.

Building	ΔP_{min} (in.w.g.)	ΔP_{max} (in.w.g.)	Number of open doors for design	Flow through closed doors (CFM)	Flow through open doors (CFM)	Flow through door opening to the outside (CFM)	Flow through Lobby door (CFM)	Flow if all doors were to be closed (Reference) (CFM)	Maximum Design Flow (CFM)
A	0.05	0.346	2	194	4353	7313	5230	1050	17092
B	0.05	0.346	7	787	9400	0	5449	2656	15635
C	0.05	0.346	9	1689	8927	9482	5472	4228	25572
D	0.05	0.346	9	1676	9697	9462	5474	4189	26310
E	0.05	0.346	8	2143	9377	9937	5421	5017	26880
F	0.05	0.346	8	1990	11696	0	5557	4680	19245

Table 2 Reference calculations for all buildings studied

4. Description of the Tests

The tests consisted of a manual start-up of the fan with all doors closed until the pressure stabilized. Once the pressure stabilized doors were opened in a random manner and the pressure was tracked as a function of time.

The pressure difference between the stair and the building was measured using a Dwyer Mark II pressure transducer and the pressures recorded every 5 seconds. The pressure was measured at the floor where the pressure sensor was placed.

The area of the inlet duct was measured and a CPS-Velocitor-AM 50 anemometer was used to record the velocity within the duct. With the area and flow velocity the value of Q was monitored as a function of time. Type K thermocouples were used to monitor the temperature inside and outside the building. The interior temperature remained between 20-21 ^{o}C while the exterior temperature between 15-17 ^{o}C. The tests were conducted while the temperature difference was very small to reduce one of the variables of the problem. The objective of conducting the tests with such a narrow temperature difference was to provide idealized conditions for control. Other information such as the fan RPM's was also collected.

Prior to the tests the fans had to be characterized, because this information was not available. For each fan an RPM vs. CFM operation curve was established. Figure 2 shows a typical curve for a fan.

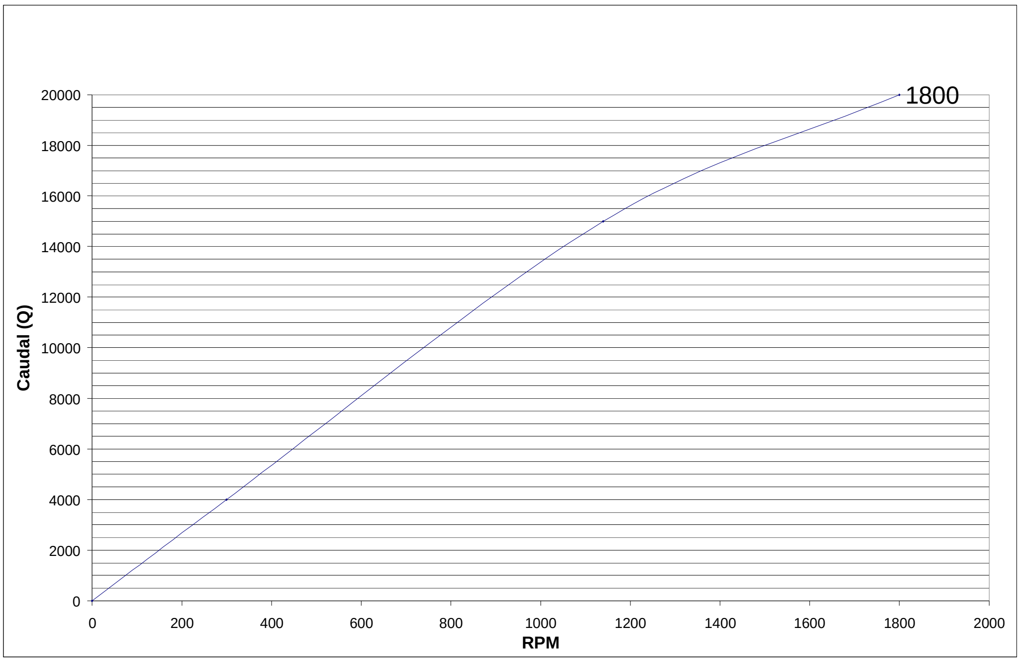

Figure 2 Characterization of a typical fan.

5. Experimental Results

A series of results for Building A will be presented to illustrate the behaviour of the pressurized staircases. The general trends were the same for all tests conducted therefore these results should be assumed to be representative of the behaviour of all buildings.

Figure 3 shows the evolution of the pressure with respect to time through the process of randomly opening the doors. The dotted lines indicate the design thresholds and the arrows the moments when doors were opened or closed. It can be observed that the initial opening of a door results in a pressure drop followed by a peak that exceeds the maximum desired pressure. The mechanical dampers are too slow to open and do not have a significant effect on the pressure. Instead the control system manages to eventually bring the pressure down and stabilize the system within the desirable range. It is important to note that stability is attained at a higher than initial pressure. A second door opening has a similar effect but without the large pressure peak, instead a minor peak is followed by a period where the controller becomes unstable but within the acceptable pressure range. For three and floor opened doors the system stabilizes below the minimum pressure required. It is important to note that the scale makes the pressure deficit look small, nevertheless, for four open doors the pressure stabilizes at about 60% below the minimum required value, thus the system will be ineffective for more than four doors open.

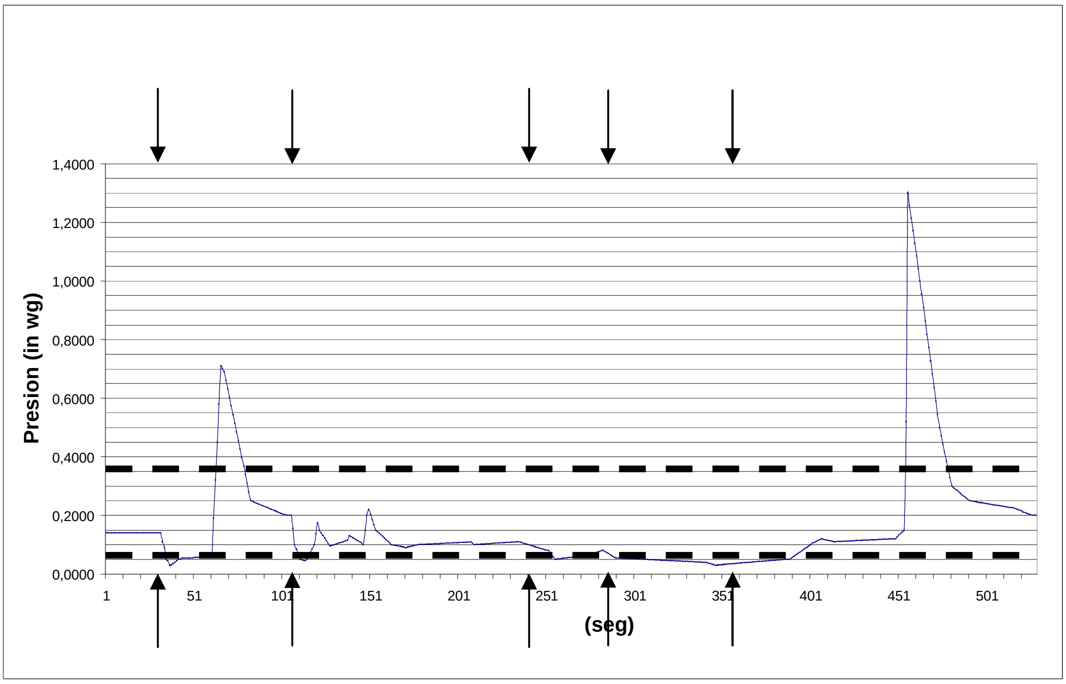

Figure 3 Pressure variation as a function of time for different number of doors open.

Finally, when the doors are closed, the pressure increases again with the mechanical dampers incapable of controlling the rise. The control system will eventually respond and stabilize the pressure, but this process can, in some cases, take more than two minutes which is extremely long when compared to typical egress periods. It is important to note that the system will not stabilize to the same pressure, thus opening and closing of doors will affect the overall leakage of the stair in a dynamic manner.

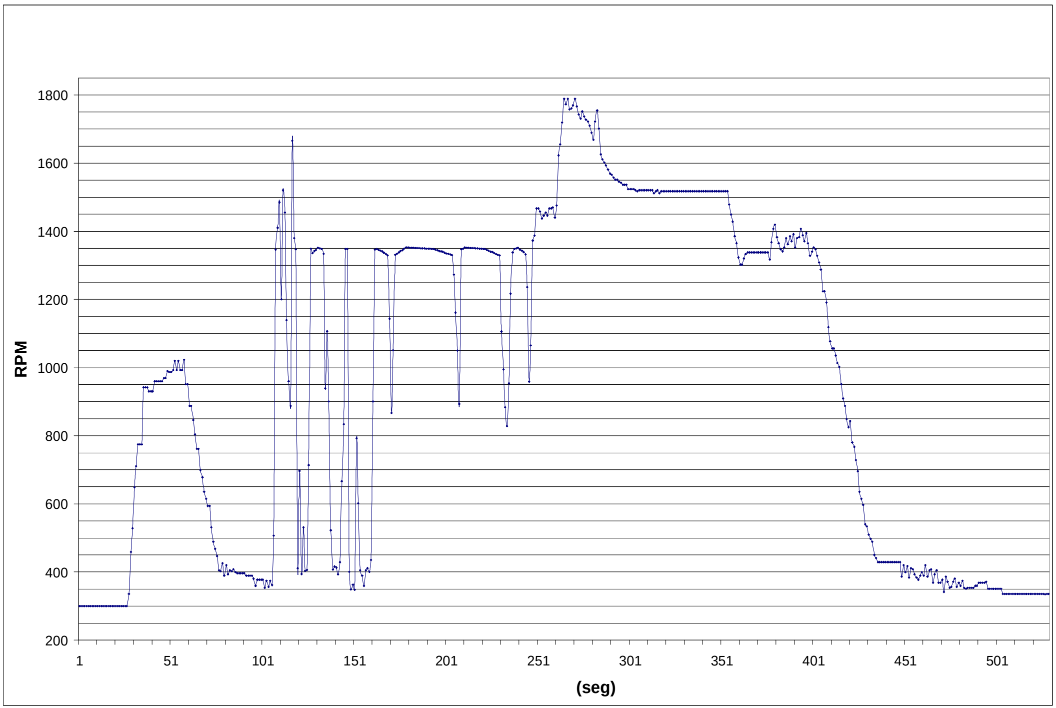

Figure 4 Revolutions per minute for the fan for through the opening and closing of the doors.

Figure 4 shows the evolution of the RPM's of the fan and the attempts of the control system to reach a stable pressure. This plot indicates that the control system becomes unstable once the second door is open and only achieves the desired pressure by drastic oscillations of the fan velocity. While the objective is attained, this is not an adequate operating mode. A similar situation occurs for three and four doors open and the system only achieves true stability when one or none of the doors are open. Similar observations were recorded for all buildings. For the taller buildings (C, D, E, F) the less drastic the fluctuations of the fan but the longer the response time of the controller. In most cases the pressure never exceeded the maximum allowed pressure. This can be easily explained by the larger volume of air within the stair that serves to dampen the response of the fan. Table 3 shows the maximum recorded pressures and it can be seen that the peak values remain below the design value of 0.35 in.w.g. In contrast, for the taller buildings, periods below the minimum required pressure could be long following the opening of a door far away from the pressure transducer.

This system can be further analyzed to understand if the entire hypothesis used in the calculations were adequate. Table 2 shows that for building "A" two conditions were calculated, all doors closed and two open doors. The requirement of the system was established to be 17,092 CFM's with two open doors and 1,050 CFM's with all doors closed. If the pressure measurements in the initial cycle are used to recalculate the different parameters obtained from tables then the requirements are 4,000 CFM's for all doors closed and 22,000 CFM's for two open doors. It is important to note that if these differences are translated to area factors for the stair to the building and for the building to the exterior; values of 0.98×10^{-3} and 0.87×10^{-4} respectively are obtained. The values obtained from the ASHRAE tables were 0.11×10^{-3} and 0.50×10^{-4} respectively. This indicates that leakage in this building is greater than what was anticipated by the design area factors. Furthermore, these factors will vary as the cycles of opening and closing of doors progress. Table 3 shows similar values for all buildings establishing that leakage was underestimated for all buildings that formed part of this study.

In the case of Building A, Figure 2 shows that the fan could not supply enough flow for the case of 2 doors open. This was not the case for all buildings. In most of the buildings the fan was capable of coping with the real flow rates. Nevertheless, the same unstable behaviour of the controller was observed even if the fan was within its operating bounds.

Finally, there are a number of other factors that were observed to significantly affect the flow rate. it was observed that many other variables such as the configuration within the office spaces affected the pressure significantly. In cases where an elevator door was open, or a door to an office was left open, the flow requirements increased even further.

Building	Minimum Measured Pressure (In.w.g.)	Maximum Measured Pressure (In.w.g.)	Flow (all doors closed) (CFM)	Calculated Flow (all doors closed) (Reference) (CFM)
A	0,030	1,30	4000	1050
B	0,040	0,40	7000	2656
C	0,070	0,17	9036	4228
D	0,045	0.10	6215	4189
E	0,045	0.18	8345	5017
F	0,045	0.22	8200	4680

Table 3 Measured values for all buildings studied

6. Conclusions

The performance of a pressurization system has been studied for a series of six real buildings. It was shown that the performance of the system was very sensitive to the different variables involved. The empirical constants used for design were shown to under define the flow required for these particular buildings. It was observed that in many cases this was partly due to inadequate finishing of the building or poor maintenance. The dampers used to cap the pressure did not perform adequately having little effect on reducing the pressure rise. Ultimately the control system maintained the pressure within the desired ranges; nevertheless, it was not done in a stable manner. For taller buildings, pressure oscillations were smaller but the reaction of the control system could lead to longer delays.

Given the sensitivity of the system to so many variables, for robustness, these systems have to be designed over dimensioning the capacity of the fan, nevertheless, this cannot be done if a simple control system is used and dampers are to deliver pressure capping. A more complex control system needs to be designed that takes into account more input variables.

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